UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

DTIC ELECTE SEP 27 1989 D B

AD-A212 677

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. ...EDULE	
4. ...MBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- ... 1245
6a. NAME OF PERFORMING ORGANIZATION Stanford University / 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFOSR/NP
6c. ADDRESS (City, State, and ZIP Code) Jordan Quad/Birch Stanford, CA 94305-4125	7b. ADDRESS (City, State, and ZIP Code) Building 410, Bolling AFB DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR / 8b. OFFICE SYMBOL (If applicable) NP	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F49620-86-K-0019
8c. ADDRESS (City, State, and ZIP Code) Building 410, Bolling AFB DC 20332-6448	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 61103D; PROJECT NO. 3484; TASK NO. A6; WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

(U) ADVANCED SOURCE DEVELOPMENT AND APPLICATIONS (JOINT PROPOSAL WITH 86NP244)

12. PERSONAL AUTHOR(S)

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 1 Oct 86 TO 30 Sep 88	July 1989	24

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	
	20.06		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The development of high average power pulsed solid-state lasers and the application of these lasers to the generation of laser produced plasmas for soft-X-ray generation is described. A 44-W average power moving slab neodymium glass laser was demonstrated. In a separate experiment, injection seeding of this laser to produce 500-MW 11-ps pulses was attained. Soft-X-ray generation has been investigated with the moving slab laser, a fix slab laser, and commercial rod-geometry lasers. The techniques that were demonstrated show the feasibility of scaling the operation of slab lasers to the kilowatt level. The rapid development of diode-laser pumping techniques suggests the potential for remarkably efficient, comopact and economical laser systems for short wavelength lithography and microscopy applications.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT x☐ UNCLASSIFIED/UNLIMITED x☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL H R Schlossberg	22b. TELEPHONE (Include Area Code) (202) 767-4906	22c. OFFICE SYMBOL AFOSR/NP

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

89 9 27 046

AFOSR-TR- 89-1245

Advanced Source Development and Applications

Laser-Produced Plasmas: A Compact Soft X-Ray Source with High Peak Brightness

Final Technical Report
Air Force Office of Scientific Research
contract F49620-86K-0019
October 1, 1986 through September 30, 1988

Robert L. Byer
Principal Investigator

July 1989

Advanced Source Development and Applications

Laser-Produced Plasmas: A Compact Soft X-Ray Source with High Peak Brightness

Robert L. Byer
Applied Physics Department
Stanford University
Stanford, California 94305

ABSTRACT

The development of high average power pulsed solid-state lasers and the application of these lasers to the generation of laser produced plasmas for soft-X-ray generation is described. A 44-W average power moving slab neodymium glass laser was demonstrated. In a separate experiment, injection seeding of this laser to produce 500-MW 11-ps pulses was attained. Soft-X-ray generation has been investigated with the moving slab laser, a fix slab laser, and commercial rod-geometry lasers. The techniques that were demonstrated show the feasibility of scaling the operation of slab lasers to the kilowatt level. The rapid development of diode-laser pumping techniques suggests the potential for remarkably efficient, compact and economical laser systems for short wavelength lithography and microscopy applications.

Advanced Source Development and Applications

Laser-Produced Plasmas: A Compact Soft X-Ray Source with High Peak Brightness

Table of Contents

Advanced Source Development and Applications

Laser-Produced Plasmas: A Compact Soft X-Ray Source with High Peak Brightness

Personnel Associated with the Program

Robert L. Byer — Principal Investigator

Robert C. Eckardt — Senior Research Associate

Eric Gustafson — Research Associate

Martin M. Fejer — Acting Assistance Professor

Santanu Basu — Ph.D., June 1988

John A. Trail — Ph.D., June 1989

Murray K. Reed — Graduate Student

Eric Szarmes — Graduate Student

Toshi Yamada — Visiting Scholar

Kazuo Maeda — Visiting Scholar

Laser-produced-plasma Soft-X-ray Source Development and Applications

I Introduction

Laser-produced-plasmas are an attractive source of soft x-ray radiation because of their comparatively low cost and laboratory size. The broadband emission from the plasma excited by a focused high power laser can have a high peak and average brightness and be useful in spectroscopy, lithography and microscopy.

The investigation of laser-produced-plasma soft-x-ray sources at Stanford University has been conducted by R.L.Byer. The work in the initial two years of this program has concentrated first on the development of high peak and average power Nd:glass zigzag slab laser sources suitable as laser-produced-plasma drivers, and also on the characterization and application of laser-produced-plasmas generated with a commercial, medium power, Nd:YAG laser. This work has shown much progress and we have completed a laser-produced-plasma soft-x-ray microscope with submicron resolution and are now close to the completion and characterization of a 100W , 10J Nd:glass slab laser suitable for commercial lithography. Our moving Nd:glass slab laser program has demonstrated the ability to scale slab lasers to multi-kilowatt average power levels and is now being extended by industrial researchers. The laser produced plasma has proved to be a versatile, compact and reliable source of soft x-rays for science and industry.

II Laser Plasma Research Facilities and Personnel

The research described in this report was conducted by R.L.Byer, Professor of Applied Physics at Ginzton Laboratory in Stanford.

Facilities purchased or developed within R.L.Byer's laboratories for the laser-produced-plasma studies include two commercial Quanta-ray Nd:YAG lasers, one of which has a single-axial-mode seeder installed for improved stability and high-peak-power operation. One of these lasers is linked to the soft-x-ray microscope vacuum system and a laser-produced-plasma target chamber designed by J.A.Trail. Two Nd:glass slab lasers, a 100 W fixed slab designed by M.K.Reed and a 50 W moving slab system designed by S.Basu, have been completed and used to generate soft-x-rays in this target chamber with increased average power. We used a high resolution grating vaccuum spectrometer for studying UV, XUV and softer x-rays and have constructed a calibrated x-ray diode and thin-film filter system for investigating radiation with photon energies of a keV and higher.

Collaboration with other laboratories has allowed us to ensure we are abreast of all developments relating to our research. The Lawrence Livermore National Laboratories have recently started a large program to develop high average power Nd:glass lasers similar to those in our lab. We have several ties to their program and have exchanged a number of visits and discussed further cooperation. The soft-x-ray microscope was coated at the Center for X-Ray Optics at the University of California's Lawrence Berkeley Laboratory. This work included the collaborative characterization of the coating deposition for curved optics in their system.

III. Laser Plasma Research Results

A. Nd:Glass Slab Laser Development

High average power operation of solid state lasers in the conventional rod geometry is limited by thermal distortions in the laser medium. These thermal lensing and depolarization effects can be avoided by using the zigzag slab geometry. Thin slabs can be efficiently cooled through large transverse faces and to first order any residual thermally induced beam distortions and depolarizations are cancelled by a zigzag laser beam path through the slab. Slab based solid state laser systems can be scaled to high repetition rates without sacrificing beam quality.

The goal of our fixed slab laser design was a high peak and average power Nd:glass laser with a polarized, low divergence output which can be focussed to produce high temperature plasmas and efficiently generate soft x-rays. Nd:glass is a laser material that has been developed extensively for laser-induced nuclear fusion projects. It is available in large sizes and is capable of generating extremely intense laser radiation. Our target laser parameters of 100 W average power with a peak intensity of 10^{13} W/cm^2 translate into 10 J in 10 ns in a 100 μm^2 at 10 Hz.

We have built a Nd:glass laser with a slab of dimensions (6 x 64 x 330) mm^3 rated to operate in a Q-switched mode at 10 joules per pulse and 10 pulses per second [9]. The total internal reflection faces of the Nd:glass slab are protected by sapphire windows and the distributions of the optical pumping and the water cooling are controlled to reduce the thermo-optic distortions of the laser beam. Present operation is with a electrical input energy of 2 kJ at 5 Hz. Under an electrical power loading of 10 kW we measure a total optical distortion in transmission through the slab of less than one optical wave across the entire laser aperture. The laser efficiency is 0.5 % of the electrical input power, or 10 J output, when operated as a full aperture planar oscillator. Q-switching with a large apreture KD*P crystal produces a laser pulse-length of about 40 ns and focussing this output with a 20 cm focal length lens in the vacuum chamber produces a spot size of (140 x 70) μm^2. Plasma production with this laser has been studied with a calibrated x-ray diode. Research continues to improve the laser beam quality and reduce the pulse length.

We have implemented the first experimental version of the moving slab Nd:glass laser. In this design a large Nd:glass slab is repetitively moved across a small pumping area to spread the thermal load while localising the gain. This offers the potential for scaling to multikilowatt average power operation. In the moving slab laser a laser slab of dimensions (167 x 150 x 4.4) mm^3 is moved back and forth between two flashlamps and large cooling plates. The laser operated with Q-switched 4.4 J output at a power supply limited 10 Hz repetition rate. Hoya Optics of Japan has continued this research and has recently demonstrated 400 W output from a very similar moving slab laser .

Recent progress in diode lasers and laser arrays has allowed their use as effective pumps for small solid state lasers. Diode pumping can result in exceptionally stable laser output. We developed cw diode-pumped monolithic Nd:YAG ring lasers for the injection seeding of our higher power lasers. These are small crystals that are polished and coated to create an internal laser cavity of a ring geometry. Careful design allows high power single-axial-mode output. Single-axial-mode seeding of the larger Q-switched lasers smooths the Q-switched temporal pulse, removing random high intensity spikes and stabilising the output. We have also developed a diode-pumped modelocked Nd:glass laser with 10ps output pulses. This has been used to injection modelock the Q-switched moving slab laser. The technique of injection seeding allows the desirable short pulse length characteristics of the diode pumped systems to be transfered to the high power slab lasers for effective plasma generation. The temporal characteristics of plasma production with the injection modelocked laser has been studied with a microchannel plate detector and shown to mimic the modelocked laser pulse structure. The moving slab laser research is the subject of the PhD thesis of S.Basu.

Research continues to complete our investigation of laser plasma soft x-ray lithography with the Nd:glass slab laser source. Pulses shorter than the free-running Q-switch length of 50 ns are essential for efficient laser to x-ray conversion. To shorten the 50 ns Q-switch pulse of the Nd:glass slab laser to 10 ns we will use pulsed injection seeding. This technique has been demonstrated in our laboratory by S. Basu using a diode-pumped modelocked Nd:glass source to seed a Nd:glass moving slab laser. We are presently developing a diode-pumped modelocked Nd:glass laser suitable for injection seeding the fixed Nd:glass slab laser. An output of ten 1ns pulses for a total pulse length of 10 ns can be expected to be close to optimum for both extraction from the Nd:glass slab laser and for x-ray production. The demonstration of high resolution lithography with the laser produced plasma source as a characterization of the commercial processing potential of laser-produced-plasma soft x-ray lithography with a high-average-power laser will be presented in the PhD thesis of M.K.Reed. We feel that demonstrating the advantages of the zigzag slab geometry laser for high peak and average power operation will lead to its wider use in scientific and industrial applications.

B. Scanning Soft- Xray Microscope Development

A compact soft-xray microscope suitable for the biological imaging of living cells has been constructed and evaluated. The microscope uses a laser-produced plasma generated by a commercial Nd:YAG rod laser on a copper target as the 14 nm wavelength soft x-ray source. Normal incidence multilayer-coated mirrors in a Schwarzschild configuration act as the focussing optics. The microscope has a spatial resolution of 0.5 microns and operates by raster scanning a sample through the focus and detecting transmitted photons. A full description of the apparatus and results obtained with it is presented in the PhD thesis of J.A.Trail.

Measurements with the Nd:YAG laser have also been made of soft x-ray radiation and debris emission for a range of target materials and laser fluences. The laser produced plasma source was also used as a broadband x-ray source for measurement of normal incidence multilayer mirror reflectance in the 10 -25 nm spectral region. Research continues on characterizing and optimizing the Schwarzchild focus using tomographic reconstruction.

Laser-Produced Plasma Soft-X-Ray Development and Applications

Related Publications and Presentations

PUBLICATIONS

1. M. K Reed, T. Yamada and R. L. Byer, "Conduction Cooling of Nd:Glass Slab Lasers," SPIE Proc. **622**, *High Power Solid State Lasers*, p. 622 (Sept. 1986).

2. S. Basu and R. L. Byer, "40-W Average Power, 30-Hz Moving Slab Nd:glass Laser," *Opt. Lett.* **11**, pp. 617-619 (Oct., 1986).

3. S. Basu, T. J. Kane and R. L. Byer, "A Proposed 1 kW Average Power Moving Slab Nd:Glass Laser," *IEEE J. Quantum Electron.* **QE-22**, pp. 2052-2057 (Oct. 1986).

4. S. Basu and R. L. Byer, "Recent Advances in Fixed Cavity, Moving Slab Lasers," Proc. SPIE **736**, *New Slab and Solid-State Laser Technologies and Applications*, pp. 34-37 (July 1987).

5. M. K. Reed and R. L. Byer, "Performance of a Conduction Cooled Nd:Glass Slab Laser," Proc. SPIE **736**, *New Slab and Solid-State Laser Technologies and Applications*, pp. 38-44 (July 1987).

6. J. A. Trail, R. L. Byer and T. W. Barbee, Jr, "Measurement of soft-x-ray multilayer mirror reflectance at normal incidence using laser produced plasmas," *Appl. Phys. Lett.* **52**, pp. 269-271 (25 Jan. 1988).

7. M. K. Reed, W. J. Kozlovsky, R. L. Byer, G. L. Harnagel and P. S. Cross, "Diode-laser-array-pumped neodymium slab oscillators," *Opt. Lett.* **13**, pp. 204-206 (March 1988).

8. S. Basu and R. L. Byer, "Continuous-wave mode-locked Nd:glass laser pumped by a laser diode," *Opt. Lett.* **13**, pp. 458-460 (June 1988).

9. Santanu Basu, "A High Peak and High Average Power Nd:Glasss Moving Slab Laser for Soft X-Ray Generation," Ph.D. dissertation, Stanford University (June 1987); Ginzton Laboratory Report No. 4244 (Stanford University, Stanford, CA, June, 1988).

10. J. A. Trail, R. L. Byer and J. B. Kortright, "The Stanford Tabletop Scanning X-ray Microscope," in *X-Ray Microscopy II*, ed. by D. Sayre, M. Howells, J. Kinz and H. Rarback (Springer-Verlag, Berlin 1988) pp 310-315.

12. J.A. Trail and R.L. Byer, "Compact scanning soft-x-ray microscope using a laser-produced plasma source and normal-incidence multilayer mirrors," *Opt. Lett.* **14**, pp. 539-541, (June 1, 1989).

12. J.A. Trail and R.L. Byer, "First Images from the Stanford Tabletop Scanning Soft X-Ray Microscope," *OSA Proceedings on Short Wavelength Coherent Radiation: Generation and Applications*, R.W. Falcone and J. Kirz, eds. (Optical Society of America, Washington, DC, 1988), Vol. 2, pp. 290-294.

SUBMITTED FOR PUBLICATION

1. S. Basu and R. L. Byer, "Injection mode-locking of Q-switched oscillators - theory and experiment," submitted to IEEE J. Quantum Electron.

PRESENTATIONS

1. J. A. Trail and R. L. Byer, Scanning Soft X-ray Microscope," SPIE Conf. 897, Scanning Microscopy Technologies and Applications, O-E/LASE '88, Los Angeles, Jan., 1988.

2. M. K. Reed, T. Yamada and R. L. Byer, "Conduction Cooling of Nd:Glass Slab Lasers," paper 622-05, Optoelectronic and Laser Applications in Science and Engineering, Los Angeles,19-24 January 1986.

3. S. Basu and R. L. Byer, "A High Average Power Moving Slab Nd:glass Laser," paper ThE4, 1986 International Laser Science Conference, Seattle, 19-24 October, 1986.

4. M. K. Reed and R. L. Byer, "Performance of a Conduction Cooled Nd:Glass Slab Laser," paper 736-8, O-E LASE '87 (SPIE), Los Angeles, 11-16 Jan. 1987.

5. S. Basu and R. L. Byer, "Diode-Laser Pumped and Mode-Locked Nd:Glass Laser," paper WN3, Conference on Lasers and Electro-Optics, Baltimore, April 27 - May 1, 1987.

6. M. K. R[illegible]., W. J. Kozlovsky, R. L. Byer, G. L. Harnagel and P. S. Cross, "Diode Laser Array Pumped Nd:YAG and Nd:Glass Laser Source," post deadline paper, Topical Meeting on Coherent Laser Radar: Technology and Applications, Aspen, Colorado, July 27-31, 1987.

7. J. A. Trail, R. L. Byer and J. B. Kortright, "The Stanford Scanning X-Ray Microscope," The International Symposium on X-Ray Microscopy, Brookhaven, August 31 - September 4, 1987.

8. S. Basu and R. L. Byer, "A Diode Pumped and Mode Locked 50 ps Nd:Glass Laser Source," presented at the 3rd International Laser Science Conference, Atlantic City, NJ, November 1 - 5, 1987.

9. J. Trail and R. L. Byer, "Scanning X-ray Microscope", paper 897-29, Optoelectronics and Laser Applications in Science and Engineering (O-E/LASE'88), Los Angeles, California, January, 1988.

10. S. Basu and R. L. Byer, "Generation of 500 mW Peak Power Pulses from an Injection Mode-Locked and Q-Swithced Nd:Glass Moving Slab Laser," paper ThV1, 1988 Conference on Lasers and Electro-Optics, Anaheim, California, April, 1988.

11. M. K. Reed and R. L. Byer, "The Performance of a Conduction Cooled Nd:Glass Zig-Zag Slab Laser," International Conference on Optical Science and Engineering, Hamburg, West Germany, Sept., 1988.

12. M. K. Reed , "Slab Lasers," (Tutorial Course) The International Conference on Optical Science and Engineerin, Hamburg, West Germany, Sept,. 1988.

13. M. K. Reed and R. L. Byer, "A Nd:Glass Slab Laser for Soft X-ray Lithography", paper MB4, Conference on Lasers and ElectroOptics (CLEO), 24-28 April 1989, Baltimore, Maryland.

A Proposed 1 kW Average Power Moving Slab Nd:Glass Laser

SANTANU BASU, THOMAS J. KANE, MEMBER, IEEE, AND ROBERT L. BYER, SENIOR MEMBER, IEEE

Abstract—The design considerations of a high average power Nd:glass slab laser in which the slab moves between the pumping lamps to distribute the thermal loading over the area of the glass while maintaining high gain in the pumped volume are presented. Continuous wave operation and high repetition rate pulsed operation are projected at the 1 kW average power level.

Introduction

The average power available from a conventional Nd:glass rod laser is severely limited by the low thermal conductivity of the glass. Thermal stress and temperature variations in the glass rod create optical distortions that limit the average power output. Also the low thermal conductivity of the glass causes thermal stress fracture when the heat dissipated by an Nd:glass rod exceeds 5 W/cm of rod length. A 4 m long rod would be required to produce an output of 1 kW average power when operated at the fracture limit. The thermal focusing of such a rod is much shorter than the rod length which makes it impractical to construct such a laser.

The zigzag slab geometry laser [1] eliminates the optical distortions and allows the average power to be increased until limited by the thermal fracture of the glass. Average power output of 25 W has been reported for a 15 × 2.5 × 0.8 cm Nd:glass slab geometry laser [2]. The low-gain cross section of Nd:glass requires strong pumping to reach threshold. The strong pumping requirement coupled with the low thermal conductivity of glass leads to pulsed Nd:glass laser operation at 1–10 Hz repetition rates.

The average power of an Nd:glass slab laser can be increased by moving the glass medium to distribute the thermal load over a large area while maintaining high gain in the small volume pumped by the lamps [3]. In this paper the feasibility of constructing a moving slab laser is discussed. The temperature and stress distributions inside the slab are calculated. The optical beam quality of the moving slab laser and the power output of a 3.3 percent Nd doped zigzag glass slab laser are calculated. The design approaches which have been undertaken at our laboratory to construct a moving slab laser are also presented.

Manuscript received May 28, 1985; revised December 2, 1985 and May 2, 1986. This work was supported by the Office of Naval Research under Contract N00014-83-K-0449.

The authors are with the Ginzton Laboratory, Stanford University, Stanford, CA 94305.

IEEE Log Number 8609681.

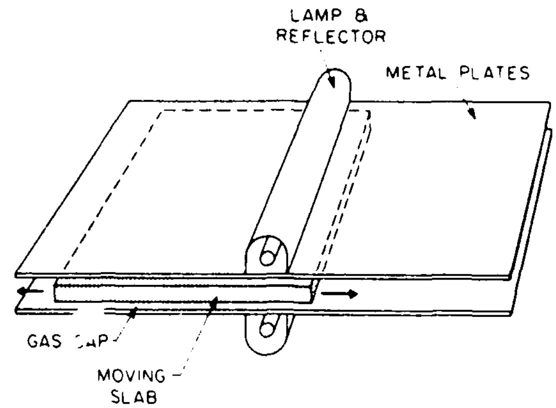

Fig. 1. The moving slab laser can be pumped above the CW threshold because cooling takes place over a large area while gain remains concentrated. Mechanical design is greatly simplified by cooling the slab through a thin layer of conductive gas rather than using flowing water.

Possible moving-slab designs include a rotating disk, a rectangular slab moving back and forth, and a rotating cylinder [4]. In our preliminary design, we have chosen a rectangular slab geometry as shown in Fig. 1. In this setup, a rectangular Nd:glass slab, with Brewster angle ends, moves back and forth between two metal cooling plates. The glass slab is contained in a holder which is moved by means of a computer-controlled linear motor. Pumping is carried out from both sides by two CW krypton arc lamps which are placed at the center of the cooling plates as shown in the figure. The lasing direction is perpendicular to the direction of slab motion. The theoretical calculations presented in this paper are based on this geometry.

This paper is intended to show that the design of a moving slab laser is feasible and a large increase in average power output from solid-state lasers is possible in this geometry. The thermal load handling capacity is directly proportional to the area of the pumping region, whereas the gain depends on the input power level, the thickness of the slab, and the efficiency of coupling the lamp radiation into the slab. For pulsed operation, the average power output is thus increased by an order of magnitude more than the corresponding static slab laser case. The increased average power handling capacity allows CW operation since the gain can be increased limited only by the available glass size and the lamp input power.

Theory

A. Thermal Considerations

The glass medium must move at a rate rapid enough to efficiently distribute the thermal load over the entire volume. For a slab medium of thickness t_g, the thermal time constant [5] is given by

$$\tau = C_p t_g^2/12k_g \qquad (1)$$

where C_p is the specific heat, k_g is the thermal conductivity, and t_g is the thickness of the glass. For a 0.44 cm thick plate of LHG-5 glass the value of τ is 7.3 s. Thus, the motion cycle time required to provide uniform heat dissipation is of the order of 1 s.

The temperature and stress distribution of the thin Nd:glass media envisioned are well approximated by a slab that is infinite in two dimensions. In the Appendix, a two dimensional temperature profile is calculated for the moving slab. The calculation confirms that the slab is approximated by a medium infinite in the transverse direction. The surface stress on the slab, cooled on both surfaces and uniformly heated, is given by Eggleston *et al.* [5] as

$$\sigma_s = Qt_g^2/12M_s \qquad (2)$$

where Q is the heat created per unit volume and

$$M_s = (1 - \nu)k_g/\alpha E \qquad (3)$$

is a material figure of merit with ν the Poisson's ratio, α the thermal expansion coefficient, and E Young's modulus.

The total thermal power dissipated in a slab is $P_t = QAt_g$ where the area $A = Lw$. Here, L is the length of the slab along the gain direction and w is the slab width. Equation (2) can be rewritten as

$$\sigma_s = P_t t_g/12M_s A. \qquad (4)$$

which illustrates the average power scaling for slab geometry lasers in the stress-fracture limited regime. If we choose to operate at the stress fracture limit, σ_{max}, then the average thermal power dissipated in the slab is given by ($\sigma_s = \sigma_{max}$)

$$P_{t,max} = 12M_s A\sigma_{max}/t_g. \qquad (5)$$

The average thermal power limit scales with the area of the slab and inversely with the slab thickness. This result holds as long as the heat dissipation is in the steady-state limit, that is, if the slab motion uniformly averages the thermal load or if pulsed lamps are flashed at a rate that exceeds the thermal response time of the medium, given by (1). The thermal power P_t which is dissipated in the slab can be estimated from published values given in [6]–[8]. The parameter χ [5], which is the ratio of the heat load and the stored energy varies between 1.2 and 2.2 for 3.3 percent Nd-doped LHG-5 glass [6]–[8]. In CW krypton arc lamp-pumped LHG-5 glass, which we consider in this paper, the match between the absorption spectrum of Nd:glass and the lamp emission spectrum is better than the corresponding case of xenon lamp pumped system at high current density. However, to be conservative in our performance projections, we take the value of χ to be 2 in our analysis.

B. Laser Performance

Of key interest is the projected gain, loss, and optical power output of the laser. When a value of the storage efficiency r is assumed, then the gain can be calculated as a function of the pump power P, the volume of the pumped material V, the path length through the pumped region, and the saturation intensity of the laser medium I_{sat}. For a zigzag slab the path length through the slab is greater than the slab length by a factor of $1/\cos(\theta)$, where θ is the angle between the laser beam and the surface of the slab. The single pass unsaturated gain is

$$\gamma = \Pr L/I_{sat}V\cos(\theta). \qquad (6)$$

If it is assumed that the pumped volume V is as wide as it is thick, so that it is related to the length and thickness of the slab by $V = Lt_g^2$, then (6) can be rewritten as

$$\gamma = \Pr/t_g^2 I_{sat}\cos(\theta). \qquad (7)$$

For moderately high-doped Nd:glass the gain is reduced by absorption due to the thermal population of the lower laser level. The gain reduction is a function of the average temperature, the neodymium ion concentration and the energy above the ground state of the lower laser level. The difference between the average temperature of the slab and the temperature at the slab surface is obtained by integrating the temperature distribution for the slab given by Eggleston *et al.* [5] as

$$T_1 = P_t t_g/12k_g A. \qquad (8)$$

This must be added to the temperature rise across the coolant gap between the slab and the surrounding cooled metal plates, as shown in Fig. 1. For conductive cooling through a thin gap of gas, the temperature rise across the gap is

$$\Delta T = P_t t_h/2k_h A \qquad (9)$$

where k_h is the conductivity of the gas and t_h is the thickness of the gap. The factor of two results from assuming cooling on both sides of the slab. The resultant average slab temperature is

$$T_{avg} = T_{coolant} + \Delta T + T_1. \qquad (10)$$

The gain reduction due to thermal population in the lower laser level is

$$\gamma_r = \int_0^{L/\cos\theta} g_1\sigma N e^{-E_2/kT}\,dz \qquad (11)$$

where σ is the cross section for stimulated emission, L is the slab length, N is the ground state neodymium ion concentration, E_2 is lower laser level energy, kT is the thermal energy, and g_1 is the degeneracy of the upper laser level. For Nd:glass the upper state degeneracy is one. In the cases under study, for a 0.44 cm thick glass slab the average glass temperature was less than 40°C. Numerical calculations showed that without introducing significant error, (11) can be simplified by replacing T by the glass average temperature. The lower laser level population reduces the amount of energy which can be extracted from the laser. Assuming that the slab is pumped uniformly, the available power, P_{avail}, is given by

$$P_{avail} = Pr(1 - \gamma_r/\gamma). \tag{12}$$

Optical losses in this type of laser are due to intrinsic scatter in the glass, and to surface scatter on the total internal reflection surfaces and other surfaces. The loss coefficient may be expressed as

$$\alpha_l = \alpha L/\cos(\theta) + \alpha_{sca} \tag{13}$$

where α is the intrinsic loss per centimeter in the glass and α_{sca} is the loss due to scatter at surfaces.

The efficiency with which the available power is converted to useful laser output is the extraction efficiency, η_{ext}. For small values of gain and loss, the extraction efficiency at optimal output coupling is given by [9]

$$\eta_{ext} = (1 - \sqrt{(\alpha_l/(\gamma - \gamma_r))})^2. \tag{14}$$

The laser output power, W is given by

$$W = \eta_{ext} P_{avail} \tag{15}$$

For large gain system, the output power is obtained by using the Rigrod analysis [10]. The output power in the large gain case for a homogeneously broadened laser is given by

$$W = \frac{t_g^2 I_{sat}(1 - R)}{1 - R + \alpha_l(1 + \sqrt{(R - \alpha_l)/(1 - \alpha_l)}} \cdot (\gamma - \gamma_r + \ln\sqrt{(R - \alpha_l)(1 - \alpha_l)}) \tag{16}$$

where R is the reflectivity of the output mirror, which is optimized for maximum W. This relation is also valid in Nd:glass, which has a very fast cross relaxation rate within the inhomogeneous line [6]. This concludes the presentation of the equations describing the projected performance of the Nd:glass moving slab laser.

TABLE I
MOVING SLAB LASER PROJECTED PERFORMANCE

Laser Parameters	15 cm Laser	60 cm Laser
Active slab length, L (cm)	15	60
Active slab width, w (cm)	24	30
Slab thickness, t_g (cm)	0.44	0.44
He gap, t_h (cm)	0.0125	0.0125
θ, deg	23.69	23.69
Cavity length (cm)	75	120
Cooling plate temperature (C)	10	10
Pumping Parameters		
Total lamp power, P (kW)	12	61.4
Storage efficiency, r	04	.04
Thermal load, P_t (kW)	0.96	4.91
Allowable thermal load, $P_{t_{max}}$ (kW)	1.52	7.62
Slab average temperature (C)	36.1	36.7
	cw Lamp Pumping	
Single pass unsaturated gain, γ	.189	.969
Gain reduction due to lower state population, γ_r	.025	.103
Single pass loss, α_l	.05	.2
Extraction efficiency, η_{ext}	.201	.211
Overall efficiency	.007	.0075
cw power output, W (W)	83.5	462
	Pulsed Lamp Pumping	
Rep rate, Hz	100	100
Pulse length, ms	1	1
Lamp pump energy per pulse, J	120	614
Output energy per pulse, J	3.46	16.5
Overall efficiency	.0288	.0269
Average power output, W	346	1650

Moving Slab Laser Performance

The projected performance of the moving slab laser is shown in Table I. The efficiency with which the lamp energy is converted into energy stored in the upper laser level is known as the storage efficiency. The storage efficiency depends on the match between the pump spectrum and the absorption of the neodymium ions, as well as on the concentration of the ions and the thickness of the laser medium. Assuming a storage efficiency of 4 percent [11]-[13], the single pass gain is 18.9 percent in a 15 cm laser at 12 kW of total input power to two 15 cm long krypton arc lamps. The average temperature of the glass is 36.1°C at this input power. The gain reduction due to ground state absorption which is a function of temperature is 2.5 percent. The CW power output is 83.5 W, as shown in Table I. Parasitic oscillation is not expected to be a major problem in the CW moving slab laser, since the inversion is confined within a small geometry and the gain is low.

For pulsed xenon flashlamp operation where the lamps operate for 1 ms duration at 10 percent duty cycle, the single-pass unsaturated gain increases to 1.89 for a storage efficiency of 4 percent. The increased gain leads to improved extraction efficiency of 73 percent, which is calculated applying Rigrod analysis [10]. The average output power is 346 W at 12 kW of average input power. The moving slab laser scales favorably to larger dimensions. For example, Table I shows that a 60 cm Nd : glass laser pumped at 61.4 kW of average input power by xenon flashlamps generates 1.65 kW at 4 percent storage efficiency.

Design Considerations

The problems of laser glass cooling and resonator alignment stability take on new aspects due to the motion of the slab. Thermal-optical distortion would be very severe at the high average powers proposed if beam propagation were straight through the slab. The zigzag ray path geometry solves the thermal-optical distortion problem, while conductive gas cooling and proper resonator design reduce the difficulty of designing a moving slab system.

The large transverse dimension of the pieces of laser glass that are envisioned very nearly meet the assumptions of the ideal infinite slab. In the infinite slab, thermal focusing and birefringence are eliminated, making possible polarized, near diffraction-limited output. However, motion of the beam due to motion of the glass may be a problem. The heating of the glass as it passes through the pumped volume will create an optical index gradient that acts like a weak prism. For a glass with small change in optical path length with temperature, such as LHG-5, the angle of beam deflection has been calculated in the appendix to be 0.95 mrad. The beam deflection can be further minimized by using an athermal glass like LGH-8, or by having two slabs moving in opposite directions. At 8 cm/s speed and at 580 cm/s^2 acceleration, which we have chosen for our design, the residence time under the lamp is 50 ms at the slab center and it is 56.9 ms at the turning points. The difference in heat load at the slab center and at the turning points can further be minimized by modulating the input power of the lamps. The maximum stress because of acceleration is 2.626×10^3 pascal which is much less than the fracture stress of glass of 2×10^7 pascal.

Gas conductive cooling substantially simplifies the construction of the moving glass laser while reducing the chances of thermal fracture operation [14]. The lamps are assumed to be water cooled, while the glass itself is cooled conductively through a thin layer of static gas that couples the slab to a sheet of water-cooled metal. The system for cooling a laser in a slab configuration is shown schematically in Fig. 1. The primary advantage of gas conductive cooling is the greater simplicity in designing the seals and the mechanical system. Small leaks are not a problem, and there is no need to separate the coolant from the beam path. The bearings that allow the slab motion are simpler if gas is the coolant. Also attractive is the fact that gas conductive cooling reduces the chance of glass fracture due to thermal shock. A sudden change in coolant temperature will not lead to a sudden change in glass temperature, as the gas only loosely couples the slab to the cooled metal.

It is possible to design the optical resonator so that the position and direction of the output beam depend only on the mirror orientation and not on small motions of the slab. For a resonator with a flat high reflectance mirror and a curved output mirror, the beam direction outside the resonator is determined by the orientation of the flat back mirror, while the beam position is determined by the curved output mirror. This resonator stability means that small slab motions are compensated, leading to a stable focal spot.

Three slab geometries have been considered. The simplest is a rectangular slab of glass which moves back and forth. The only disadvantage is that the motion for such a slab results in a discontinuity at the turning points. Another geometry is the rotating disk. The disk moves continuously, but must have a larger area than the slab because the slow-moving center cannot be effectively cooled and thus cannot be pumped. A third possibility, which combines the advantages of continuous motion and uniform heating, is a cylinder of glass rotating around its axis. If fabrication were possible, this would be the best design from thermal considerations.

Conclusion

We have presented design calculations for a moving slab laser that confirm the potential advantages of this approach for high average and peak power operation of solid state lasers. The advantages of the approach include the use of high optical quality laser glass instead of crystals, as the gain medium and potential scaling to high average power levels.

We believe that the mechanical problems of the moving glass slab laser are not particularly difficult to solve and that the moving slab concept can be scaled to very high average powers. The moving slab laser is capable of generating greater than 1 kW average power in a small laser volume. The high average power has applications in various industrial laser processing operations. The 60 cm moving slab laser can also be mode-locked and Q-switched to produce sufficiently high peak power to generate laser driven plasmas from suitable target materials. For efficient X-ray generation, the laser must be able to deliver 10^{13}–10^{15} W/cm^2 on a target in 100 ps to 1 ns pulses. We expect that the moving slab laser, which can deliver high intensity pulses at high repetition rate, will be a convenient source for soft X-ray generation for X-ray lithography, and X-ray microscopy applications [15], [16].

Appendix
Temperature Distribution In a Moving Slab

In this Appendix the temperature profile in the moving slab is calculated. The end effects (in the axial direction) are not included in the analysis. Fig. 2(a) shows a cross section of the slab which is pumped by two lamps.

The heat balance equations are given by

$$\partial T/\partial t = (k_g/\rho C_p)(\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2) - V_x \partial T/\partial x + Q_1/\rho C_p; \quad 0 \le y \le t_g/2 \quad \text{(A1)}$$

$$Q_1 = 0 \quad \text{for} \quad x < 0 \quad \text{and for} \quad x > d \quad \text{(A2)}$$

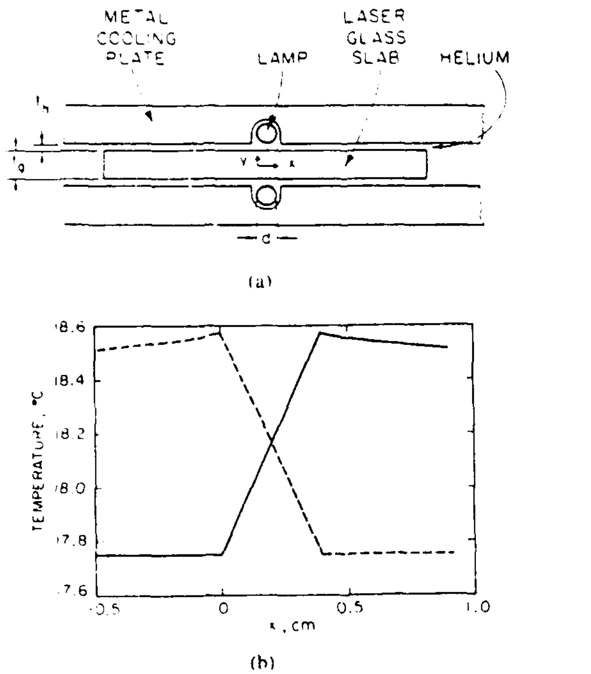

Fig. 2. (a) The cross section of the moving slab laser. (b) Temperature on the glass surface as a function of x. The solid line represents the case when the slab is moving to the right and the broken line is when the slab is moving to the left.

$$Q_1 = P_l/Ldt_g; \quad 0 < x < d \tag{A3}$$

where ρ is the density of glass and d is the lamp diameter. An equation similar to (A1) can be written for helium in the gap between the glass and the metal cooling plate. But since the gap is very small, $\partial^2T/\partial y^2$ term is much larger than the other terms. Therefore, little error is introduced if it is assumed that at any instant the temperature profile in helium is linear. The boundary conditions are

$$\partial T/\partial y = 0 \quad \text{at} \quad y = 0 \tag{A4}$$

$$\partial T/\partial x = 0 \quad \text{at} \quad |x| \gg d \tag{A5}$$

$$-k_g \partial T/\partial y = -k_h \partial T/\partial y \quad \text{at} \quad y = t_g/2 \tag{A6}$$

$$T = T_{\text{coolant}} \quad \text{at} \quad y = t_h + t_g/2. \tag{A7}$$

The solution to these equations has been obtained numerically. For reducing the computational efforts we have assumed that the steady-state temperature profiles have been attained in the slab at all x at $t = 0$. Thus the initial conditions are given by

$$T = T_{\text{coolant}} + (Qt_gt_h/2k_h) + (Q/8k_g)(t_g^2 - 4y^2);$$
$$0 < y < t_g/2 \tag{A8}$$

$$T = T_{\text{coolant}} + (Qt_g/2k_h)(t_h + t_g/2 - y);$$
$$t_g/2 < y < t_h + t_g/2 \tag{A9}$$

where $Q = P_l/Lwt_g$. It was found that starting with these initial conditions, the temperature profile repeats itself after a few cycles of slab motion. The temperature profile in the y direction is parabolic. The maximum temperature difference in the glass slab is 24.8°C for the case of 60 cm laser with 4 percent storage efficiency. For zigzag beam propagation, this quadratic temperature variation is experienced by each ray and hence thermal focusing is avoided. The temperature profile in the direction of slab motion at the glass surface has been plotted in Fig. 2(b) for two consecutive cycles. The average temperature gradient is 2.41°C/cm. The beam steering due to the transverse temperature gradient has been estimated for a 1.22 m long resonator formed by a 3 m radius mirror and a flat mirror. The deviation of a ray which is intially along the resonator axis has been calculated after one round trip. The maximum deviation has been found to be 0.569 mm on either side of the resonator axis depending on the direction of slab motion. This corresponds to a net angular deviation of 0.95 mrad. For comparison, the angular sensitivity to mirror misalignment of this resonator for an aperture of 0.44 cm which is the glass thickness [6, p. 191] is 1.47 mrad. For an athermal glass like LHG-8, the net angular deviation is 0.13 mrad. However, in either case symmetric motion of two counter moving glass slabs eliminates all beam steering to first order.

References

[1] G. J. Hulme and W. B. Jones, "Total internal reflection face pumped laser," *Soc. Photo-Opt. Instr. Eng.*, vol. 69, pp. 38-45, 1975.

[2] J. M. Eggleston, T. J. Kane, J. Unternahrer, and R. L. Byer, "Slab-geometry Nd:glass laser performance studies," *Opt. Lett.*, vol. 7, pp. 405-407, 1982.

[3] T. J. Kane and R. L. Byer, "Proposed kilowatt-average-power Nd:glass laser," *J. Opt. Soc. Amer.*, vol. 72, p. 1755, 1982.

[4] R. L. Byer, "High average power solid state laser," U.S. Patent 4 555 786, Nov. 1985.

[5] J. M. Eggleston, T. J. Kane, K. Kuhn, J. Unternahrer, and R. L. Byer, "The slab geometry laser. I—Theory," *IEEE J. Quantum Electron.*, vol. QE-20, pp. 289-301, Mar. 1984.

[6] W. Koechner, *Solid State Laser Engineering*. New York: Springer, 1976.

[7] M. S. Mangir and D. A. Rockwell, "Measurements of heating and energy storage in flashlamp pumped Nd:YAG and Nd-doped phosphate laser glasses," *IEEE J. Quantum Electron.*, vol. QE-22, pp. 574-580, Apr. 1986.

[8] T. J. Kane, J. M. Eggleston, and R. L. Byer, "The slab geometry laser—Part II: Thermal effects in a finite slab," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 1195-1209, Aug. 1985.

[9] A. E. Siegman, *An Introduction to Lasers and Masers*. New York: McGraw-Hill, 1971.

[10] W. W. Rigrod, "Saturation effects in high gain lasers," *J. Appl. Phys.*, vol. 36, pp. 2487-2490, 1965.

[11] J. M. Eggleston, T. Kane, K. Kuhn, and R. L. Byer, "Progress in slab geometry solid state lasers," *SPIE*, vol. 335, Advanced Laser Technology and Applications, pp. 104-108, 1982.

[12] P. Laporta, V. Magni, and O. Svelto, "Comparative study of the optical pumping efficiency in solid state lasers," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 1211-1218, Aug. 1983.

[13] J. F. Holzrichter and W. H. Lowdermilk, "Advanced laser development," in Laser Program Ann. Rep., UCRL-50021-84, pp. 6-9, 1984.

[14] M. Reed, K. Kuhn, J. Unternahrer, and R. L. Byer, "Static gas conduction cooled slab geometry Nd:glass laser," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 412-414, 1985.

[15] D. J. Nagel, "Characteristics and uses of X-radiation from laser heated plasmas," *Proc. SPIE*, "X-ray lithography and applications of soft X-rays to technology," p. 17, 1983.

[16] R. L. Byer *et al.*, "Progress in high peak power lasers for soft X-ray generation," *Proc. SPIE*, "X-ray lithography and applications of soft X-rays to technology," pp. 2-7, 1983.

Santanu Basu was born in Calcutta, India, in 1957. He received the B.Tech (Hons.) degree in chemical engineering from Indian Institute of Technology, Kharagpur, in 1978, the M.S. degree in chemical engineering from Case Institute of Technology, Cleveland, OH, in 1979, the M.S. degree in mathematics, and the M.S. degree in applied physics from Stanford University, Stanford, CA, in 1981 and 1984, respectively.

He worked for Raychem Corporation, Menlo Park, CA, from 1979 to 1984, where he was a group leader in research and development. Since 1984 he has been a doctoral student in applied physics at Stanford University and his Ph.D. dissertation is the construction of a laser plasma generated X-ray source for lithography.

Thomas J. Kane (S'82-M'85) was born in 1955. He received the B.S. degree in physics from the University of California at Davis in 1978.

In 1979 he began graduate study with the Department of Electrical Engineering, Stanford University, Stanford, CA, and in 1980 he joined the research group of Prof. Robert L. Byer. In addition to work on slab-geometry solid-state lasers, he has contributed to the development of frequency-stable diode-pumped miniature Nd:YAG lasers. His Ph.D. dissertation project is the construction of a coherent Doppler LIDAR system using Nd:YAG technology.

Robert L. Byer (M'75-SM'83) received the Ph.D. degree in applied physics from Stanford University, Stanford, CA, in 1969.

His early and continuing interest has been nonlinear interactions including harmonic generation and parametric oscillators. After joining the Applied Physics Department at Stanford, he began research in remote sensing using tunable laser sources. Research in that area led to the development of the unstable resonator Nd:YAG laser and to high-power tunable infrared generation in $LiNbO_3$ parametric tuners. In 1974 he and his colleagues initiated research in coherent anti-Stokes Raman spectroscopy (CARS), named the effect, and continued research in high-resolution Raman spectroscopy. In 1976 he suggested the use of stimulated Raman scattering in hydrogen gas to generate 16 μm radiation from a CO_2 laser source. Research at Stanford University confirmed the expected simplicity and efficiency of the approach. In 1980 research on slab geometry solid-state laser sources was begun. The program has led to successful theoretical and experimental development in high-peak and average-power solid-state laser sources. Research in advanced solid-state laser sources is continuing. He has worked in industry at Spectra Physics (1964-1965), Chromatix (1969-1974), helped found Quanta Ray Inc., in 1975 and today consults for Newport Inc., Hoya Optics, Spectra Technology, and Lightwave Electronics Corporation. He was Chairman of the Applied Physics Department at Stanford from 1981 to 1984, and was appointed Associate Dean of Humanities and Sciences in 1985.

Dr. Byer is a member of AAAS, APS, a Fellow of the OSA, and was President of the IEEE Lasers and Electro-Optics Society for 1985.

40-W average power, 30-Hz moving-slab Nd:glass laser

Santanu Basu and Robert L. Byer

Ginzton Laboratory, Stanford University, Stanford, California 94305

Received June 6, 1986; accepted July 28, 1986

A moving-slab-geometry Nd:glass laser has been designed and demonstrated. An average power output of 43.8 W has been achieved at 2.76-kW input power and at 2.06% slope efficiency. The moving-slab laser has the potential for scaling to kilowatt average power levels.

The slab-geometry solid-state laser was first proposed by Martin and Chernoch in 1972.[1] In the high-average-power operation, the zigzag slab configuration overcomes two problems of rod lasers, namely, the elimination of stress-induced birefringence by geometry and the elimination of thermal- and stress-induced focusing by a zigzag optical path.[2-4]

We report the operation of a moving-slab-geometry laser.[5] In the moving-slab laser, the average thermal power is dissipated over the area of the slab, while the gain is concentrated in a small region. The result is a gain enhancement and ease of extracting the laser energy while maintaining average power scaling as the area of the slab. Under proper conditions, cw operation is projected for the Nd:glass moving-slab-laser source.[6]

The average laser output power P_{ave} of a slab laser moving rapidly enough to average the thermal load over the area of the slab is given by[3]

$$P_{\mathrm{ave}} = 12\eta_{ex} f R_s A / t_g \chi, \tag{1}$$

where A is the pumped area of the slab, t_g is the glass thickness, χ is the ratio of the pump energy that is dissipated as heat in the laser medium to the energy that is stored in the upper laser level, and f is the ratio of the maximum stress to the fracture stress of the Nd:glass slab. The maximum possible average power output is then obtained by operating the laser at maximum storage efficiency η_{ex} and at a maximum repetition rate not exceeding the thermal stress-fracture limit of the laser medium. Here R_s is a material thermal shock parameter, which is given by[3]

$$R_s = \sigma_{\max}(1-\nu)k_g/\alpha E, \tag{2}$$

where α is the thermal expansion coefficient, E is Young's modulus, ν is the Poisson ratio, k_g is the thermal conductivity, and $\sigma_{\max}$ is the stress-fracture limit of the glass medium. R_s for LHG-5 Nd:glass is 17.9 W/m, compared with a value of 790 for Nd:YAG.

The residence time of any part of the slab under the lamps must be less than the thermal time constant. The thermal time constant τ is given by

$$\tau = C_p t_g^2/12k_g, \tag{3}$$

where C_p is the specific heat. For a 0.44-cm-thick LHG-5 Nd:glass slab, τ is 7.3 sec. The lamp power that is dissipated as heat, P_t, is 1 to 2.2 times the energy stored in the upper laser level[4,7,8] and is less than 8% of the total lamp power input. For 10-kW lamp power pumping a 0.44-cm-thick LHG-5 glass slab, the minimum area required for heat removal is 164 cm^2, assuming that 8% of the lamp input power is dissipated as heat in the Nd:glass medium. If 15-cm-long lamps were used, the glass would remain under the stress-fracture limit if the heat were dissipated over a width of 10.9 cm. In our experiment we used a Brewster-angle-cut, zigzag-path rectilinear slab of 3.3% doped LHG-5 glass of dimensions 16.7 cm × 15 cm × 0.44 cm. The current slab has been tested with cw lamp pumping to 7.3 kW of average power without fracture.

A schematic of the moving-slab laser is shown in Fig. 1. The glass was held in a frame and moved between two water-cooled metal plates. The gap between the glass and the metal plates was filled with static helium gas at atmospheric pressure, which acted as the heat-conducting medium.[9] This cooling method simplified the design of the laser at some reduction in overall efficiency owing to Fresnel reflections. Two 15-cm-long 4-mm-diameter krypton lamps pumped the

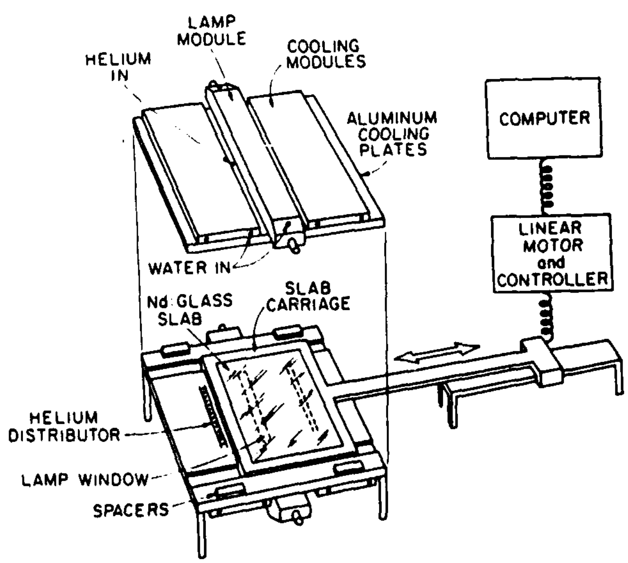

Fig. 1. Diagram of the moving-slab laser showing an exploded view schematic of the linear-motor-driven slab module and cooling approach.

0146-9592/86/100617-03$2.00/0

Nd:glass slab from both sides. The detachable lamp modules were water cooled and were separated from the glass slab by 2-mm-thick Pyrex windows. Both silver and gold elliptical lamp reflectors were tested. The length of the slab under the lamp was 13.8 cm, and the ends were shaded to minimize the end effects. The glass was housed in a carriage, which moved on cross roller ways by means of a computer-controlled linear motor. The glass speed could be varied between 0 and 50 cm/sec at a programmed velocity profile. For most of the measurements, the Nd:glass slab was moved at a speed of 0.5 cm/sec over a distance of 5 cm and at an acceleration of 147 cm/sec^2 at the turning points. The residence time of the slab under the lamps was 80 msec at the slab center and 80.2 msec at the slab ends.

Figure 2 shows the measured laser output energy versus input energy for both the gold and the silver reflectors. The laser resonator consisted of a 3-m-radius high-reflector mirror and a 40% reflectance flat output coupler. When the silver reflectors were used 4.89 J of output energy was obtained at 309 J of lamp energy at 347 μsec FWHM. The slope efficiency was 2.06%, and the wall plug efficiency was 1.58%. The slope efficiency was 1.97% for the gold reflectors.

From the threshold versus output mirror reflectance data, the round-trip loss in the Nd:glass slab was calculated to be 18.5%. The round-trip exponential gain coefficient was calculated to be $2\gamma = 0.0138 J_{in}$ for the silver reflectors and $2\gamma = 0.0126 J_{in}$ for the gold reflectors, where J_{in} is the electrical input energy into the lamps in joules.

From the slope efficiency and the threshold data, an average storage efficiency of 2.63% was calculated for the silver reflectors and 2.52% for the gold reflectors with a 40% output coupler. In our experiment, the

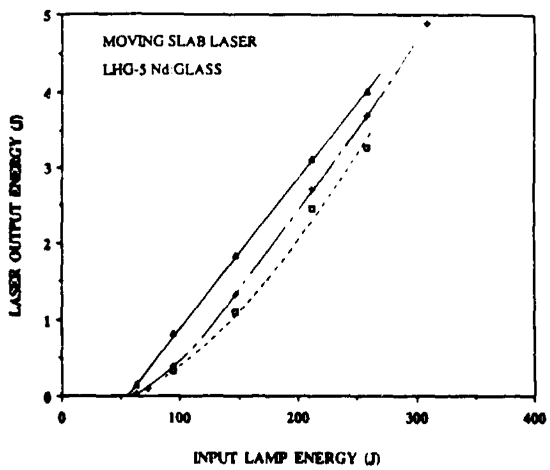

Fig. 2. Laser output energy versus pump energy. 13.8 cm of a 16.7 cm × 15 cm × 0.44 cm 3.3% doped LHG-5 Nd:glass slab was pumped by two 15-cm krypton lamps at 2 Hz. The lamps and the glass slab were separated by 1.72 cm. Both silver and gold reflectors were tested in the lamp reflector assembly. The resonator consisted of a 3-m high reflector and a flat output coupler separated by 89.5 cm. Δ, Silver reflector with 25% T output mirror; +, silver reflector with 40% T output mirror; □, gold reflector with a 40% transmission output mirror.

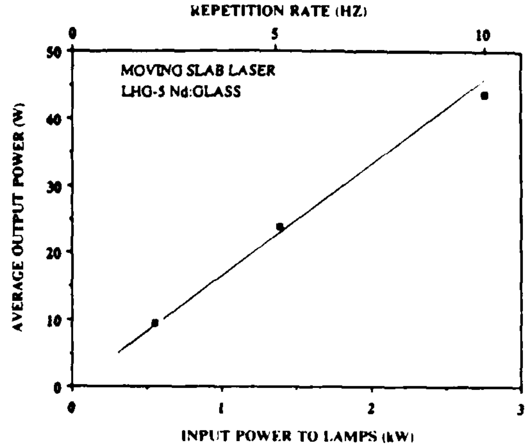

Fig. 3. Laser output versus lamp power input. The lamps were pumped at 276 J/pulse, yielding a multimode laser output of 4.38 J/pulse. Average output power was 43.8 W, which was limited by the available power supply. The laser can operate at up to 10 kW of input power.

lamp pulse length τ_{pulse} was greater than the upper-state lifetime for LHG-5 glass, which is 290 μsec.[7]

The laser oscillated in multitransverse modes, with the laser beam at the output mirror being 4 mm × 7 mm in size at the highest power level. Gas-conductive cooling substantially simplifies the design and the operation of the moving-slab laser and also provides long lifetime for the glass slab. The lamp geometry was a double elliptical cavity with two lamps focusing on the slab. Improved lamp coupling could be achieved with fluid in place of helium gas but at a cost in design complexity for fluid containment.

Figure 3 shows the laser output power as a function of the electrical power into the lamps. We obtained 43.8 W of average laser power at 2.76 kW of input power to the lamps at an overall efficiency of 1.58%. The glass was moved 10 cm in each direction. The heat dissipation was estimated to be 221 W, which was 32.8% of the allowable heat load calculated by using Eq. (1). At a 30-Hz repetition rate at 92 J/pulse into the lamps, the laser output was 13.5 W.

Moving the gain medium is unusual for solid-state lasers, and we were aware of a number of concerns about beam steering, operational problems at the turn around points, and spatial-mode quality. To study these effects, a series of measurements was carried out in the TEM_{00} mode operation using an aperture for spatial mode control. In the TEM_{00} operation with gold reflectors, 213 mJ of energy was obtained at 258.4-J input energy with an output mirror reflectance of 60%. The calculated divergence for this geometry was 0.98 mrad. A series of 40 TEM_{00} output pulses was superimposed upon a stationary black photographic paper. The measurement clearly showed the absence of beam steering due to the slab motion. The superimposed spot size at 2.26 m from the output mirror was 3.5 mm in diameter, compared with the individual spots, which were 3 mm in diameter. This amounts to less than 0.24 mrad of steering for the TEM_{00} mode. In 62 sec of operation, which included

3.1 round trips and 125 laser pulses, the variation in the output was less than 5.2%. This is comparable with power fluctuations in fixed slab and rod geometry solid-state lasers. Laser operation was not affected at the turn-around points. In the multimode laser operation, the maximum divergence of the output beam as estimated from the burn pattern on a photographic paper was 2.16 mrad. We calculated the beam brightness[7] to be 14.1 GW/cm^2 sr in the TEM_{00} mode and 2.25 GW/cm^2 sr in the multimode case.

The laser threshold was measured as a function of the cooling-plate temperature. The threshold energy was reduced from 37 to 35.2 J by reducing the temperature of the metal cooling plates from 36.5 to 8.5°C. The gain reduction due to the ground-state absorption, γ_r is given by

$$\gamma_r = \sigma(L/\cos\theta)N \exp(-E_2/kT), \tag{4}$$

where σ is the cross section, L is the length of the glass slab, N is the number density of the Nd ions in glass, E_2 is the energy of the lower state in Nd:glass, and T is the average temperature of the glass. The threshold energy has been found to be linear with the inverse of the gain reduction, $(\gamma - \gamma_r)/\gamma$, where γ is the single-pass unsaturated gain. From the cooling-plate temperature, $(\gamma - \gamma_r)/\gamma$ was calculated to be 0.96 at 8.5°C and 0.89 at 36.5°C. The gain reduction due to the lower-state absorption is not a significant problem if the glass average temperature is kept below 40°C.

The laser was Q switched by using a standard KD*P Pockels cell. For a 112-cm-long cavity with a 3-m high reflector and a flat 55% output coupler, 458 mJ of output energy in 50-nsec pulses was obtained in multimode operation at 258-J/pulse input energy at a 2-Hz repetition rate. Second-harmonic generation was carried out using a KD*P crystal, which was placed 25 cm from the output mirror without any focusing. 65 mJ of the second harmonic was obtained at 16 MW of peak power in the fundamental at a conversion efficiency of 14.2%. It is to be noted that the second-harmonic generation was used to determine the moving-slab laser beam quality, and it was not optimized for maximum conversion.

The most promising aspect of the moving-slab laser is its capability for very-high-average-power operation in a polarized output beam of very high brightness. Assuming 14 cm of glass travel, which is possible in the current design, the laser can operate at up to 10 kW of input lamp power at 84% of maximum heat load. At 276 J of lamp energy per pulse at 36 Hz, the projected power output from the current laser is 157 W.

A 1-kW average power Nd:glass moving-slab laser can be designed based on the experimental results presented in this Letter. The laser would consist of two LHG-5 Nd:glass slabs of dimensions 35 cm × 30 cm × 0.55 cm pumped by four 30-cm lamps of 6-mm diameter following the design in this Letter repeated over two sections. It is possible to increase the storage efficiency by at least 25% by bringing the lamps closer to the slab and optimizing the design. The single-pass fractional loss is estimated to be 32%. At 60% output mirror reflectance, the threshold energy is calculated to be 96 J. At a slope efficiency of 1.76% and at 1100 J/pulse into four lamps, the laser energy output has been calculated by using Rigrod analysis[10] to be 17.7 J/pulse. At 60 Hz of operation, the average laser output power is projected to be 1.06 kW. The thermal loading into the glass slabs would be 5.28 kW. The allowable thermal loading for 28 cm of glass slab travel is 6.02 kW, assuming that 8% of the pump energy is dissipated as heat in the moving slab.

In a moving-slab laser, the power-handling capacity of the glass laser is increased substantially, and hence cw operation is possible.[6] The moving-slab laser is also capable of producing short Q-switched and mode-locked pulses to produce high peak power. The high peak power has application in generating soft x rays from a laser plasma when the output is focused upon a suitable target.[11,12] The moving-slab laser, which is capable of generating high-peak-power pulses at high repetition rates, is an ideal source for x-ray lithography and microscopy and for pumping short-wavelength lasers.

In conclusion, a moving-slab-geometry Nd:glass laser has been demonstrated that utilizes a simple design. The Nd:glass slab was moved between the flash lamps and two metal cooling plates by a linear motor. The glass was static gas conduction cooled by helium gas. At the limit of the available power supply, 43.8 W of laser output power was obtained at 1.58% overall efficiency. Beam steering due to the slab motion was negligible, and laser oscillation was not interrupted at the turning points. The current design has the capability of producing 157-W laser output at 10 kW of lamp power.

The authors acknowledge the technical assistance of E. Szarmes. This research was supported by the U.S. Office of Naval Research under contract N00014-83-K-0449.

References

1. W. S. Martin and J. P. Chernoch, "Multiple internal reflection face pumped laser," U.S. Patent 3,633,126 (January 1972).
2. J. M. Eggleston, T. J. Kane, J. Unternahrer, and R. L. Byer, Opt. Lett. 7, 405 (1982).
3. J. M. Eggleston, T. J. Kane, K. Kuhn, J. Unternahrer, and R. L. Byer, IEEE J. Quantum Electron. **QE-20,** 289 (1984).
4. T. J. Kane, J. M. Eggleston, and R. L. Byer, IEEE J. Quantum Electron. **QE-21,** 1195 (1985).
5. T. J. Kane and R. L. Byer, J. Opt. Soc. Am. **72,** 1755 (1982).
6. S. Basu, T. J. Kane, and R. L. Byer, "A proposed 1-kW average power Nd:glass moving slab laser," IEEE J. Quantum Electron. (to be published).
7. W. Koechner, *Solid State Laser Engineering* (Springer, New York, 1976).
8. M. S. Mangir and D. A. Rockwell, IEEE J. Quantum Electron. **QE-22,** 574 (1986).
9. M. Reed, K. Kuhn, J. Unternahrer, and R. L. Byer, IEEE J. Quantum Electron. **QE-21,** 412 (1985).
10. W. W. Rigrod, J. Appl. Phys. **36,** 2487 (1965).
11. D. J. Nagel, Proc. Soc. Photo-Opt. Instrum. Eng. **448,** 17 (1983).
12. J. A. Trail and R. L. Byer, Proc. Soc. Photo-Opt. Instrum. Eng. **563,** 90 (1985).

736 07

A fixed Cavity, Moving Slab Nd:Glass Laser

Santanu Basu and Robert L. Byer

Ginzton Laboratory, Stanford University
California 94305

Abstract

A moving slab geometry Nd:Glass laser is capable of operating at much beyond the thermal stress fracture limit for a conventional fixed slab laser. Average power output of 43.8 W input power and at 2.06% slope efficiency in the first prototype. The moving slab laser has the potential for scaling to kilowatt average power levels.

The slab geometry solid state laser was first proposed by Martin and Chernoch in 1972[1]. The zig-zag slab configuration overcomes two problems of rod lasers, namely the elimination of stress induced birefringence by geometry and the elimination of thermal and stress induced focusing by a zig-zag optical path.[2-4]

In this paper we report the operation of a moving slab geometry laser. In the moving slab laser, the average thermal power is dissipated over the area of the slab while the gain is concentrated in a small region. The result is a gain enhancement and ease of extracting the laser energy while maintaining average power scaling as the area of the slab.

The average laser output power P_{ave} of a slab laser moving rapidly enough to average the thermal load over the area of the slab, and operating at the thermal stress fracture limit is given by[3]

$$P_{ave} = 12\, \eta_{ex}\, b\, R_s\, A / t_g\, \chi \qquad (1)$$

where A is the pumped area of the slab, t_g is the glass thickness, χ is the ratio of the pump energy which is dissipated as heat in the laser medium to the energy which is stored in the upper laser level and b is the ratio of the maximum stress to the fracture stress of the Nd:Glass slab. The maximum possible average power output it then obtained by operating the laser at maximum extraction efficiency, η_{ex} and at the maximum repetition rate not exceeding the thermal stress fracture limit of the laser medium. Here R_s is a material thermal shock parameter which is given by[3]

$$R_s = \sigma_{max}\, (1 - v) k_g\, / \, \alpha E \qquad (2)$$

where α is the thermal expansion coefficient, E is the Young's modulus, v is the Poisson ratio, k_g is the thermal conductivity and σ_{max} is the stress fracture limit of the glass medium. R_s for LHG-5 Nd:Glass is 75 W/m as compated to a value of 790 for Nd:YAG.

To dissipate the heat load over the area of the moving slab, the residence time of any part of the slab under the lamps must be less than the thermal time constant. The thermal time constant τ is given by

$$\tau = C_p t_g{}^2 / 12 k_g \qquad (3)$$

where C_p is the specific heat. For an 0.44 cm thick LHG-5 Nd:Glass slab, τ is 7.3 s. The lamp power which is dissipated as heat, P_t is 1 to 2.2 times the energy stored in the upper laser level[4] and is less than 8% of the total lamp power input. For 10 kW lamp power pumping a 0.44 cm thick LHG-5 glass slab, the minimum area required for heat removal is 156 cm^2 assuming 8% of the lamp input power is dissipated as heat in the Nd:Glass medium and operating at 25% of the maximum allowable stress value. If 15 cm long lamps were used, the glass would remain under the allowed stress limit if the heat is dissipated over a width of 10.4 cm. In our experiment we used a Brewster angle cut, zig-zag path rectilinear slab of 3.3% doped LHG-5 glass of dimension 16.7 cm x 15 cm x 0.44 cm. The current slab has been tested with cw lamp pumping to 7.3 kW of average power without fracture.

A schematic of the moving slab laser is shown in Fig. 1. The glass was held in a frame and was moved between two water cooled metal plates. The gap between the glass and the metal plates was filled with static helium gas at atmospheric pressure which acted as the heat conducting medium. This cooling method simplified the design of the laser at some reduction in overall efficiency due to Fresnel reflections. Two 15 cm long 4 mm diameter Krypton lamps pumped the Nd:Glass slab from both sides. The detachable lamp modules were water cooled and were separated from the glass slab by 2 mm thick pyrex windows. Both silver and the gold elliptical lamp reflectors were tested. The length of the slab under the lamp was 13.8 cm and the ends were shaded to minimize the end effects. The glass was housed in a carriage which moved on cross roller ways by means of a computer controlled linear motor. The glass speed could be varied between 0 and 50 cm/s at a programmed velocity profile. For the present experiments, we used a trapezoidal velocity profile with a constant velocity during most of the travel and a constant acceleration at the ends. For most of the measurements, the Nd:Glass slab was moved at a speed of 0.5 cm/s over a distance of 5 cm and at an acceleration of 147 cm/s^2 at the turning points. The residence time of the slab under the lamps was 80 ms at the slab center and 80.2 ms at the slab ends.

The laser resonator consisted of a 3 ms radius high reflector mirror and a 40% reflectance flat output coupler. Using the silver reflectors, 4.89J of output energy was obtained at 309J of lamp energy at 347 μs FWHM. The slope efficiency was 2.06% and the wall plug efficiency was 1.58%. The slope efficiency was 1.97% for the gold reflectors.

From the threshold vs output mirror reflectance data, the round trip loss in the Nd:Glass slab was calculated to be 18.5%. The round trip exponential gain coefficient was calculated to be $2\gamma = .0138J_{in}$ for the silver reflectors and $2\gamma = .0126J_{in}$ for the gold reflectors where J_{in} is the electrical input energy into the lamps in Joules.

From the slope efficiency and the threshold data, an average storage efficiency of 2.63% was calculated for the silver reflectors and 2.52% for the gold reflectors with a 40% output coupler. In our experiment, the lamp pulse length τ_{pulse} was greater than the upper state lifetime for LHG-5 glass, which is 290 μs. Approximately 70% of the lamp energy was delivered in less than 290 μs. The laser oscillated in multi-transverse modes with the laser beam at the output mirror being 4 mm x 17 mm in size as measured by the burn profile on a black photographic paper.

Gas conductive cooling substantially simplifies the design and the operation of the moving slab laser and also provides long lifetime for the glass slab. The lamp geometry was a double elliptical cavity with two lamps focusing on the slab. The distance between the lamp center and the slab center was 1.72 cm. With proper design it is possible to reduce this distance to 1.3 cm which should improve the laser efficiency. Improved lamp coupling could be achieved with fluid in place of helium gas but at a cost in design complexity for fluid containment.

Figure 2 shows the laser output power as a function of the electrical power into the lamps. We obtained 43.8W of average laser power at 2.76 kW of input power to the lamps at an overall efficiency of 1.58%. The glass was moved 10 cm in each direction. The heat dissipation was estimated to be 221 W, which was 7.8% of the allowable heat load. At 30 Hz rep. rate at 92 J/pulse into the lamps, the laser output was 13.5 W. The gain reduction due to the lower state absorption is not a significant problem since the estimated glass average temperature was kept below 40 C.

Moving the gain medium is unusual for solid state lasers and we were aware of a number of concerns about beam steering, operational problems at the turn around points and spatial mode quality. To study these effects, a series of measurements were carried out. First an aperture was placed inside the cavity to operate the laser in a single axial mode. In the single axial mode operation with gold reflectors, 213 mJ was obtained at 258.4 J input energy with an output mirror reflectance of 60%. The calculated divergence for this geometry was 0.98 mrad. A series of 40 output pulses were superimposed on a stationary black photographic paper. The superimposed spot size at 2.26 m from the output mirror was 3.5 mm in diameter as compared to the individual spots which were 3 mm in diameter. This amounts to less than 0.24 mrad of steering. In 62 seconds of operation which included 3.1 round trips and 125 laser pulses, the variation in the output was less than 5.2%. This is comparable to power fluctuations in fixed slab and rod geometry solid state lasers. Laser operation was not affected at the turn around points. In the multimode laser operation, the maximum divergence of the output beam as estimated from the burn pattern on a photographic paper was 2.16 mrad. We calculated the beam brightness to be 14.1 GW/cm^2 sr in the TEM_{00} mode and 2.25 GW/cm^2 sr in the multimode case.

The laser was Q-switched using a standard KD*P pockels cell. For a 112 cm long cavity with a 3 m HR and a flat 55% output coupler, 458 mJ of output energy in 50 ns pulses was obtained in multimode operation at 258 J/pulse input energy at 2 Hz rep. rate. Second harmonic generation was carried out using a KD*P crystal which was placed at 25 cm from the output mirror without any focusing. 65 mJ of the second harmonic was obtained at 16 MW of peak power in the fundamental at a conversion efficiency of 14.2%. It is to be noted that the second harmonic generation was used to determine the moving slab laser beam quality and it was not optimized for maximum conversion.

The most promising aspect of the moving slab laser is its capability for very high average power operation in a polarized output beam of very high brightness. Assuming 14 cm of glass travel which is possible in the current design, the laser can operate at up to 10 kW of input lamp power at 20% of maximum fracture stress level. At 276 J of lamp energy per pulse at 36 Hz, the projected power output from the current laser is 157 W.

A 450W average power Nd:Glass moving slab laser is being constructed based on the experimental results presented in this paper. The laser will consists of one LHG-5 Nd:Glass slab of dimension 30 cm x 32 cm x 0.65 cm pumped by two 25 cm lamps of 8 mm diameter. It is possible to increase the storage efficiency by at least 25% by bringing the lamps closer to the slab and optimizing the design. The single pass fractional loss is estimated to be 18%. At 50% output mirror reflectance, the threshold energy is calculated to be 70 J. At a slope efficiency of 2.1% and at 400 J/pulse into two lamps, the laser energy output has been calculated to be 7 J/pulse. At 64 Hz of operation, the average laser output power is projected to be 448 W. The thermal loading into the glass slabs would be 1.54 kW. The allowable thermal loading for 30 cm of glass slab travel is 2.62 kW assuming operation at 25% of the stress fracture limit.

In a moving slab laser, the power handling capacity of the glass laser is increased substantially and hence cw operation is possible.[5] The moving slab laser is also capable of producing very short Q-switched and mode locked pulses to produce high peak power. The high peak power has application in generating soft X-rays from a laser plasma when the output is focused on a suitable target. The moving slab laser which is capable of high peak power pulses at high repetition rates is an ideal source for X-ray lithography and microscopy and for pumping short wavelength lasers.

In conclusion, a moving slab geometry Nd:Glass laser has been demonstrated that utilizes a simple design. The Nd:Glass slab was moved between the flashlamps and two metal cooling plates by a linear motor. The glass was static gas conduction cooled by helium gas. At the limit of the available power supply, 43.8W of laser output power was obtained at 1.58% overall efficiency. Beam steering due to the slab motion was negligible and laser oscillation was not interrupted at the turning points. The beam dimensions were 4 mm x 17 mm at the maximum output energy. 213 mJ of TEM_{00} output was obtained. The current design has the capability of producing 157 W laser output at 10 kW of lamp power.

This research was supported by the Office of Naval Research, under contract N00014-83-K-0449.

References

1. Martin, W.S., Chernoch, J.P., "Multiple Internal Reflection Face Pumped Laser", U.S. Patent 3,633,126, 1972.
2. Eggleston, J.M., Kane, T.J., Unternahrer, J., and Byer, R.L., "Slab Geometry Nd:Glass Laser Performance Studies", Opt. Lett., vol. 7, pp.405-407, 1982.
3. Eggleston, J.M., Kane, T.J., Kuhn, K., Unternahrer., J., and Byer, R.L., "The Slab Geometry Laser - Part I : Theory", IEEE J. Quant. Electr. vol. QE-20, pp.289-301, March 1984.
4. Kane, T.J., Eggleston, J.M., Byer, R.L., "The Slab Geometry Laser - Part II:Thermal Effects in a Finite Slab", IEEE J. Quant. Electr. vol. QE-21, pp.1195-1209, August 1985.
5. Basu, S., Kane, T.J., and Byer, R.L., "A 1 kw Average Power Nd:Glass Moving Slab Laser", to be published in IEEE Journ. Quant. Electr. October, 1986.

Reprinted from Optics Letters, Vol. 13, page 458, June 1988.

Continuous-wave mode-locked Nd:glass laser pumped by a laser diode

Santanu Basu and Robert L. Byer

Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

Received October 20, 1987; accepted March 10, 1988

We have demonstrated a diode-laser-pumped, cw, mode-locked Nd:glass laser oscillator. With a 0.5% output coupler the pump threshold for mode-locked operation was 22.9 mW. The mode-locked pulse width was shorter than 36.5 psec, which was the response time of the fast photodiode and the sampling oscilloscope. Diode-laser-pumped mode-locked operation was also extended to Nd:YAG.

Mode-locked Nd:glass lasers traditionally have been built as water-cooled, flash-lamp-pumped, pulsed sources. The recent availability of high-power cw GaAlAs diode lasers emitting at 800 nm permits the construction of diode-laser-pumped, cw, Nd:glass laser sources.[1] We report successful operation of a 30-mW cw diode-laser-pumped, mode-locked Nd:glass laser oscillator. The mode-locked oscillator produced pulses shorter than 36.5 psec, the time response of the fast photodiode detection system. A 10-psec pulse width was estimated from autocorrelation measurements by simultaneous pumping with the diode laser and a dye laser. The same oscillator, when pumped by a 500-mW cw dye laser, generated pulses as short as 5.8 psec.

Mode-locked operation of Nd:glass was previously obtained under cw pumping with an argon-ion laser source.[2] Active mode locking of a pulsed Nd:glass laser by using an electro-optic deflector recently generated trains of 6-psec pulses.[3] Mode-locked operation of Nd:YAG (Ref. 4) with diode laser pumping and $Nd_{0.5}La_{0.5}P_5O_{14}$ (Ref. 5) with argon-ion laser pumping has also been demonstrated. The prospect of diode laser pumping of Nd:glass did not appear to be promising because of the 1-order-of-magnitude smaller gain cross section of Nd:glass compared with Nd:YAG. However, the Nd:glass medium also has lower loss and higher absorption at diode laser wavelength than Nd:YAG, such that the gain-to-loss ratio, which is the factor important in determining threshold, is similar for Nd:YAG and Nd:glass. This was recently confirmed by the successful cw diode laser pumping of Nd:glass.[1] The wide gain bandwidth of Nd:glass compared with Nd:YAG should lead to order-of-magnitude shorter mode-locked pulse widths.

Figure 1 shows a schematic of the experiment. The diode laser pump source is collimated and focused into a Brewster-angle-oriented 3-mm-thick disk of LG-760 Nd:glass with 4% doping. The active medium is placed at the focus of a three-mirror cavity, which is designed to minimize pumping threshold by minimizing the focal volume.[6] The use of a Brewster plate eliminated the need for a special coating on the gain medium and permitted easy interchange of the gain media. The design of the three-mirror cavity is similar to that widely used in cw dye laser sources.[7] The advantages of this resonator include a cavity length long enough to accommodate commercially available acousto-optic mode lockers with frequencies in the range of 30 to 150 MHz; a small spot size within the gain medium, which leads to a low pumping threshold; the capability to adjust cavity length without affecting the spot size in the gain medium; and the potential for pump multiplexing by dual-sided pumping to obtain higher average power output.

The standing-wave acousto-optic mode locker made by Newport EOS used in our experiment had a modulation index[8] $\Delta_m = 0.13$ at 1 W of rf power at 1055 nm. The resonator length was 86.27 cm to correspond with 86.9-MHz mode-locker frequency. The astigmatism of the oblique-incidence center mirror was compensated for by the astigmatism of the Brewster-angle plate at an included angle[7] 2θ, given by

$$(n^2 + 1)^{0.5}(n^2 - 1)/n^4 = (R/2t)\sin\theta\tan\theta, \qquad (1)$$

where n and t are the refractive index and the thickness of the gain medium, respectively, and R is the radius of curvature of the center mirror. In our case 2θ was 16.7°. The stability range, defined as the

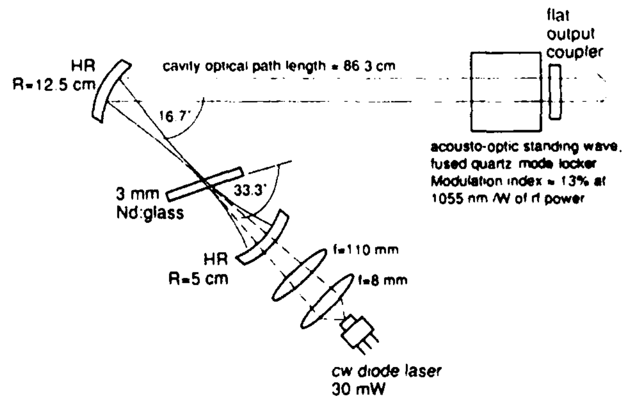

Fig. 1. Experimental setup of a diode-laser-pumped and mode-locked Nd:glass laser. The laser can be simultaneously pumped by a diode laser and a dye laser focusing through the high-reflectivity (HR) turning mirror into the gain medium, which is at Brewster angle in a three-mirror cavity.

0146-9592/88/060458-03$2.00/0

amount by which the length of the short leg of the cavity can be changed without affecting the resonator stability, is given by $2S = R^2/4d_2$, where d_2 is the length of the long arm of the cavity. The confocal parameter is given by $b = 2S$. In the present setup, $b = 2S = 0.52$ cm. For a 3-mm-thick gain medium, the resonator spot size remains almost constant through the length of the gain medium, and the position of the gain medium can be varied by as much as 1 mm without significantly increasing the oscillation threshold. The TEM_{00} mode spot size was calculated to be 29.5 μm by 45 μm with a geometrical average of 36.5 μm. The focused spot dimension in Nd:glass was 27 μm by 59 μm with a geometrical average of 40 μm.

The pump power threshold P_{th} and the slope efficiency η_s of an end-pumped laser are given by[9]

$$P_{th} = (Lh\nu_p/4\sigma\tau\eta_a)[\pi(w^2 + w_p^2)] \times \exp[2\Delta x^2/(w^2 + w_p^2)], \quad (2)$$

$$\eta_s = (T/L)(\lambda_p/\lambda)\eta_a, \quad (3)$$

where L is the round-trip cavity loss, T is the output mirror transmission, ν_p is the pump frequency, σ is the emission cross section, τ is the fluorescence lifetime, η_a is the efficiency of absorption of the pump light, λ_p and λ are the pump wavelength and the laser wavelength, respectively, w and w_p are the resonator and pump spot sizes, respectively, in the gain medium, and Δx is the mismatch distance between the resonator and the pump spots in the gain medium.

The Nd:glass laser was pumped by a 30-mW cw single-stripe diode laser, which was temperature tuned to operate at the 802-nm pump absorption band. 80% of the diode laser power was incident upon the gain medium and was absorbed completely. The internal cavity loss was measured to be 1.43%. With a 0.5% output coupler, the threshold was 15.5 mW and the slope efficiency was 9.1%. By using the expressions given in Eqs. (2) and (3) and by assuming perfectly overlapping pump and resonator beams, the threshold and the slope efficiency were calculated to be 9.6 mW and 15.7%, respectively. The difference between the calculated and the actual results is attributed to the small residual mismatch between the pump focal spot and the resonator beam in the gain medium.

The diode-pumped cw Nd:glass laser was mode locked by applying 0.4 W of rf power. The laser oscillation threshold was 22.9 mW of diode laser power. The output was 0.3 mW at 27.6 mW of diode laser power. The mode-locked laser output was detected by using a fast InGaAs photodiode,[10] which had a responsivity of 0.4 A/W at 1055 nm and a 3-dB rolloff at 22 GHz. The measuring setup, which consisted of the detector, the sampling module, and the connectors, had a measured rise time of 36.5 psec. At close to optimum mode-locking condition, the output pulse on the sampling scope had ringing and distortion, which suggested that the pulse width was shorter than 36.5 psec. A 2.9-GHz-bandwidth spectrum analyzer was used to observe in real time the axial mode mixing spectrum of the mode-locked laser. At near-optimum mode-locking condition, 16 beat notes were observed covering the range of the spectrum analyzer. A commercial autocorrelator, Femtochrome Research Model FR103, which is based on nonlinear second-harmonic generation at a 20-Hz repetition rate, was also used to measure the mode-locked pulse width. The scan range of this particular autocorrelator was 100 psec, and the pulse-width resolution was 50 fsec.

In our experiments, it was found that good mode-locking operation depended to a great extent on the cavity length and the position and orientation of the acousto-optic mode locker. Near the optimum mode-locker position and cavity length, coherence spikes on top of broad autocorrelation signals were observed. By further optimizing the position of the mode locker and the cavity length, a clean autocorrelation trace was obtained with a zero baseline, indicating the absence of a coherence spike. The transition to a smooth autocorrelation trace was accompanied by a considerable increase in the second-harmonic power generated in a $LiIO_3$ crystal. It was observed that the photodiode output as seen on a sampling scope went from a smooth pulse with ringing to a noisy pulse with considerable ringing when the transition to the shortest pulse was indicated by the autocorrelation measurement.

The output average power of 0.3 mW as obtained by pumping with a 30-mW diode laser was not enough to produce a clean signal on the autocorrelator. However, in the three-mirror cavity shown in Fig. 1 it was possible to increase the output power by pumping the gain medium simultaneously with a diode laser through the end mirror and with a dye laser through the center mirror. By separately noting the threshold with the diode laser and the dye laser, it was possible to express the combined input power in terms of an equivalent diode laser power. We decided to estimate the diode-laser-pumped mode-locked laser pulse width by making autocorrelation measurements at different values of equivalent diode laser power. Figure 2(a) shows an autocorrelation trace obtained by pumping with 41 mW of equivalent diode laser power, which was generated by 27.4 mW of diode laser power (the remaining power coming from the dye laser). The trace FWHM was 13.7 psec, corresponding to a Gaussian pulse width of 9.7 psec. When the pump power was increased to 63.1 mW, the pulse width decreased by a small amount to 9 psec. By extrapolating from these measurements at two different power levels, the pulse width obtained by 27.4 mW of diode laser pumping alone was estimated to be 10 psec.

It was of interest to find the shortest pulse that we could obtain in our setup by pumping with a much higher average power cw Rhodamine 6G dye laser and at higher rf power to the acousto-optic mode locker. With a 590-nm Rhodamine 6G dye laser as the pump source, the threshold for mode locking was 110 mW at 1.2 W of rf power to the mode locker. The FWHM of the autocorrelation trace was 8.2 psec. For a Gaussian pulse shape, this indicates a FWHM of 5.8 psec for the mode-locked pulse. This to our knowledge is the shortest pulse produced by active mode locking of Nd:glass. At 440 mW of dye laser power, the output power was 13 mW, and the peak power was 12.9 W.

In another experiment, the Nd:glass laser piece was

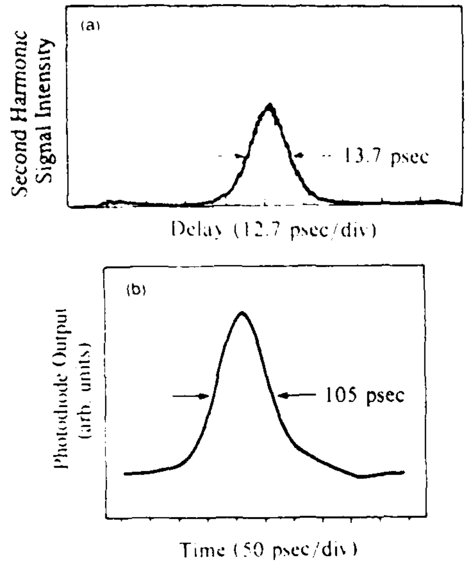

Fig. 2. (a) Second-harmonic-generation autocorrelation trace of a cw pumped and mode-locked Nd:glass laser, pumped by a combination of a cw diode laser and a cw Rhodamine 6G dye laser. The 27.4-mW diode laser provided 66.8% of the total pump power. Horizontal scale, 12.76 psec/division. Pulse FWHM is estimated to be 9.7 psec, corresponding to the trace FWHM of 13.7 psec assuming a Gaussian pulse shape. (b) Mode-locked output of a 20-mW cw diode-laser-pumped Nd:YAG laser as detected by an InGaAs photodiode and displayed on a sampling scope. Pulse FWHM 105 psec.

replaced by a 3-mm-thick Nd:YAG crystal. An estimated 59% of the diode laser light was absorbed in the gain medium. At 1 W of rf power and with a threshold of 18.7 mW of diode laser power, 105-psec pulses were obtained from the mode-locked Nd:YAG laser, as shown in Fig. 2(b).

The Nd:YAG laser was also pumped by a dye laser, and the rf power to the mode locker was varied. The pulse width was calculated from the homogeneous mode-locking theory.[8] At low rf power levels, the pulse width varied in accordance with the homogeneous mode-locking theory. At greater than 0.6 W of rf, the smooth pulse envelope broke to give shorter pulses. The minimum pulse width obtained with 150 mW of dye laser pumping was 58 psec FWHM at 1 W of rf power. The mode-locking threshold was at 30.5 mW of dye laser power at 1 W of rf power.

The combination of the short gain medium with low loss, and with low material dispersion, large gain bandwidth of Nd:glass, and an efficient and stable diode laser as the pump source, produces short mode-locked pulses at high overall efficiency. This cavity is also unique in the sense that large cw pump power can be tolerated without thermal problems by slowly rotating and translating the disk and uniformly pumping over a large area. For example, the maximum temperature rise in a uniformly pumped Nd:glass disk of 1-cm radius and 2.5-mm thickness is calculated to be 16°C for pumping by 50 W of average diode laser power. It is possible to increase the pump power in this three-mirror geometry to 4 W by polarization multiplexing four 1-W gain-guided single-stripe diode lasers.[11,12] For 200-μm spot size for both the resonator and the pump beams at the gain medium, the optimum output coupling is 7% for a round-trip internal loss of 4.8%. The laser threshold is calculated to be 1.6 W, and the output power at 4 W of pump power is estimated to be 0.85 W. The circulating peak intensity at the gain medium is calculated to be 8.7 MW/cm^2, which is expected to produce the same 5.8-psec pulse width as was obtained in our dye-laser-pumped Nd:glass laser, for which the peak intensity was 61 MW/cm^2. The shortest possible pulse width in Nd:glass is approximately 0.13 psec, which is difficult to obtain in active mode locking because of the cavity synchronism requirement. Assuming a 5.8-psec cw mode-locked pulse width the peak power is projected to be 0.83 kW, which will permit pulse compression to 90 fsec in a two-stage fiber-grating pulse compressor.[13]

It should be noted that this mode-locked laser source required no cooling water and operated at less than 30 W of input electrical power. To demonstrate the low input power requirements, the mode-locked Nd:glass laser was also run from a rechargeable battery, which had the capacity of providing continuous power to the laser diode, the thermoelectric cooler, and the rf driver for more than 2 h. Possible applications of such a solid-state mode-locked source are in electro-optic sampling and in frequency conversion. This diode-laser-pumped and mode-locked source is also an ideal source for chirped pulse amplification[14] and for injection mode locking of Q-switched oscillators,[15] both of which generate high peak power.

References

1. W. Kozlovsky, T. Y. Fan, and R. L. Byer, Opt. Lett. **11**, 788 (1986).
2. L. Yan, J. D. Ling, P.-T. Ho, and C. H. Lee, Opt. Lett. **11**, 502 (1986).
3. A. Morimoto, T. Kobayashi, and T. Sueta, IEEE J. Quantum Electron. **QE-24**, 94 (1988).
4. I. P. Alcock and A. I. Ferguson, Opt. Commun. **58**, 417 (1986).
5. S. R. Chinn and W. K. Zwicker, Appl. Phys. Lett. **34**, 847 (1979).
6. M. J. F. Digonnet and C. J. Gaeta, Appl. Opt. **24**, 333 (1985).
7. H. Kogelnik, E. P. Ippen, A. Dienes, and C. V. Shank, IEEE J. Quantum Electron. **QE-8**, 373 (1972).
8. D. J. Kuizenga and A. E. Siegman, IEEE J. Quantum Electron. **QE-6**, 694 (1970).
9. K. Kubodera, K. Otsuka, and S. Miyazawa, Appl. Opt. **18**, 884 (1979).
10. C. A. Barrus, J. E. Bowers, and R. S. Tucker, Electron. Lett. **21**, 262 (1985).
11. Sony Semiconductor Data Book, *AlGaAs Laser Diodes* (1987).
12. Spectra Diode Labs. Model SDL-2460 data sheet (1987).
13. W. J. Tomlinson, R. H. Stolen, and C. V. Shank, J. Opt. Soc. Am. B **1**, 139 (1984).
14. D. Strickland and G. Mourou, Opt. Commun. **55**, 447 (1985).
15. S. Basu and R. L. Byer, "Injection mode-locking of Q-switched oscillators—theory and experiment," submitted to J. Quantum Electron.